Physics of the Heavy Flavor Tracker at STAR

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Physics of the Heavy Flavor Tracker at STAR

1) Au+Au collisions

- measure heavy-quark hadron v_2, the heavy-quark collectivity to study light-quark thermalization
- measure heavy-quark energy loss to study pQCD in hot/dense medium
- measure di-leptions to study the direct radiation from the hot/dens medium

2) p+p collisions

- measure energy dependence of the heavy-quark production
- measure gluon structure with heavy quarks and direct photons

Outline

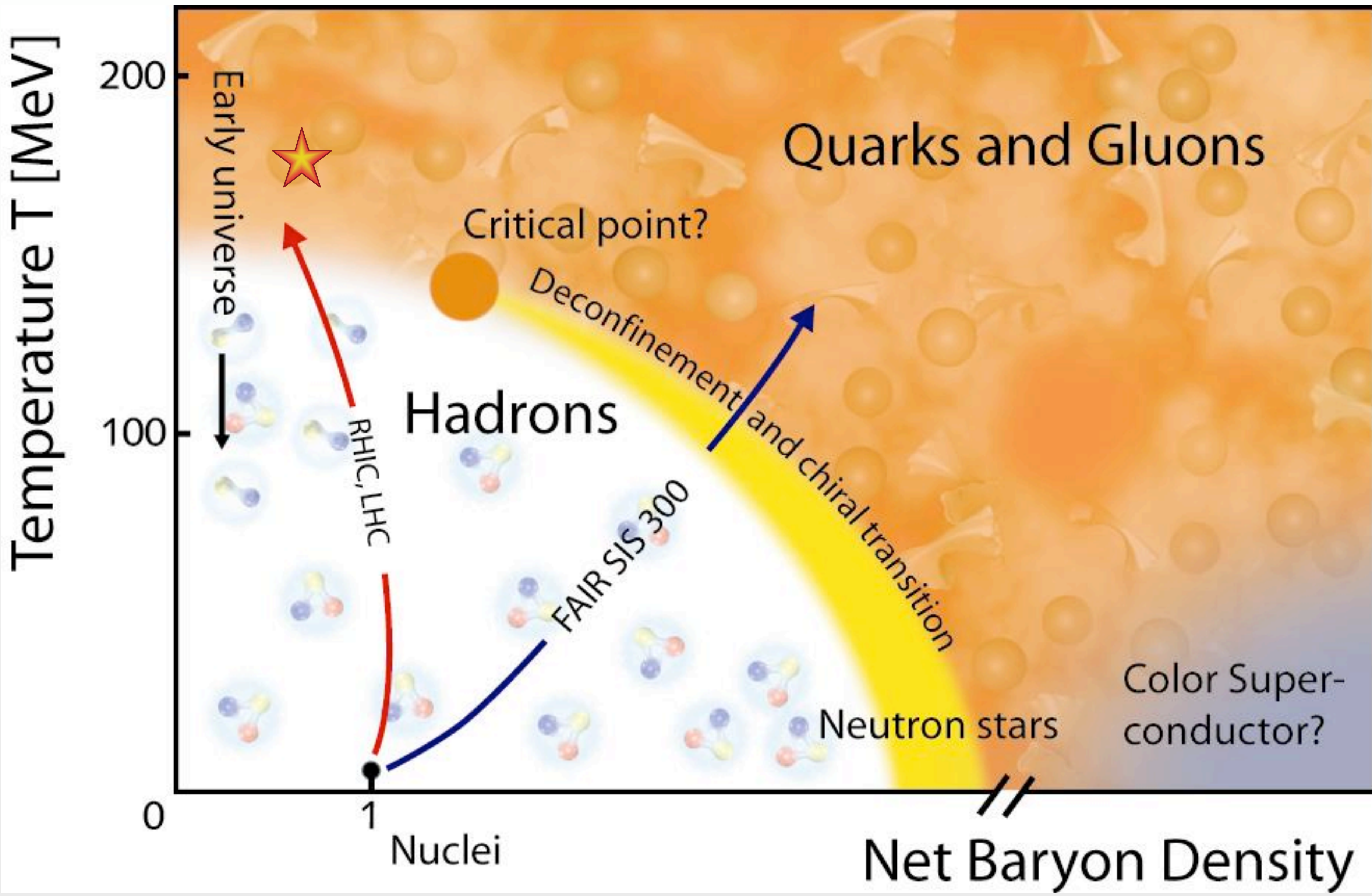
1) Introduction
   - Recent results from RHIC: R_{AA} and v_2

2) New frontier - heavy quark production
   - HQ collectivity: test light quark thermalization
   - HQ energy loss: test pQCD in hot/dense medium

3) Proton helicity structure at RHIC

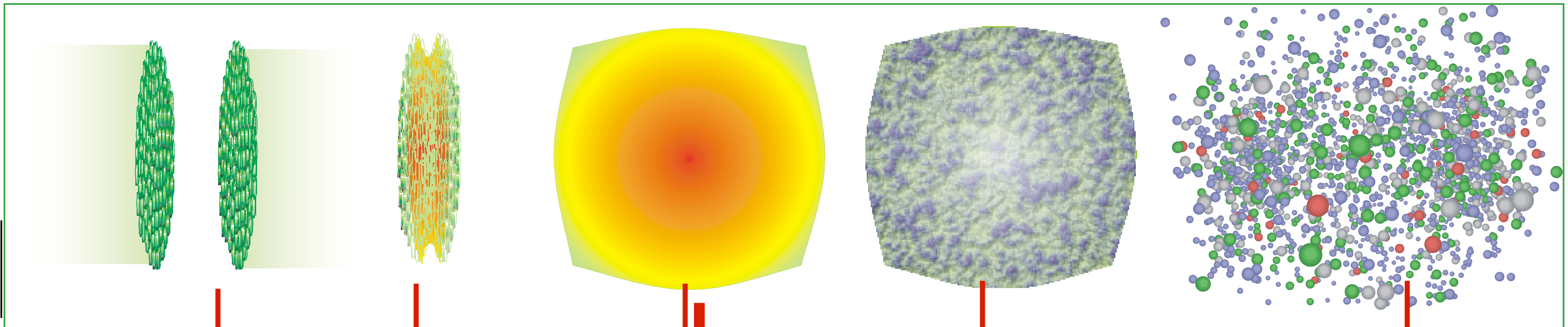
4) The numbers

The QCD Phase Diagram



Take from P. Senger

High-energy Nuclear Collisions



S. Bass

Initial conditions

Initial high Q^2 interactions

Parton matter - QGP - The hot-QCD

Hadronization and Freeze-out

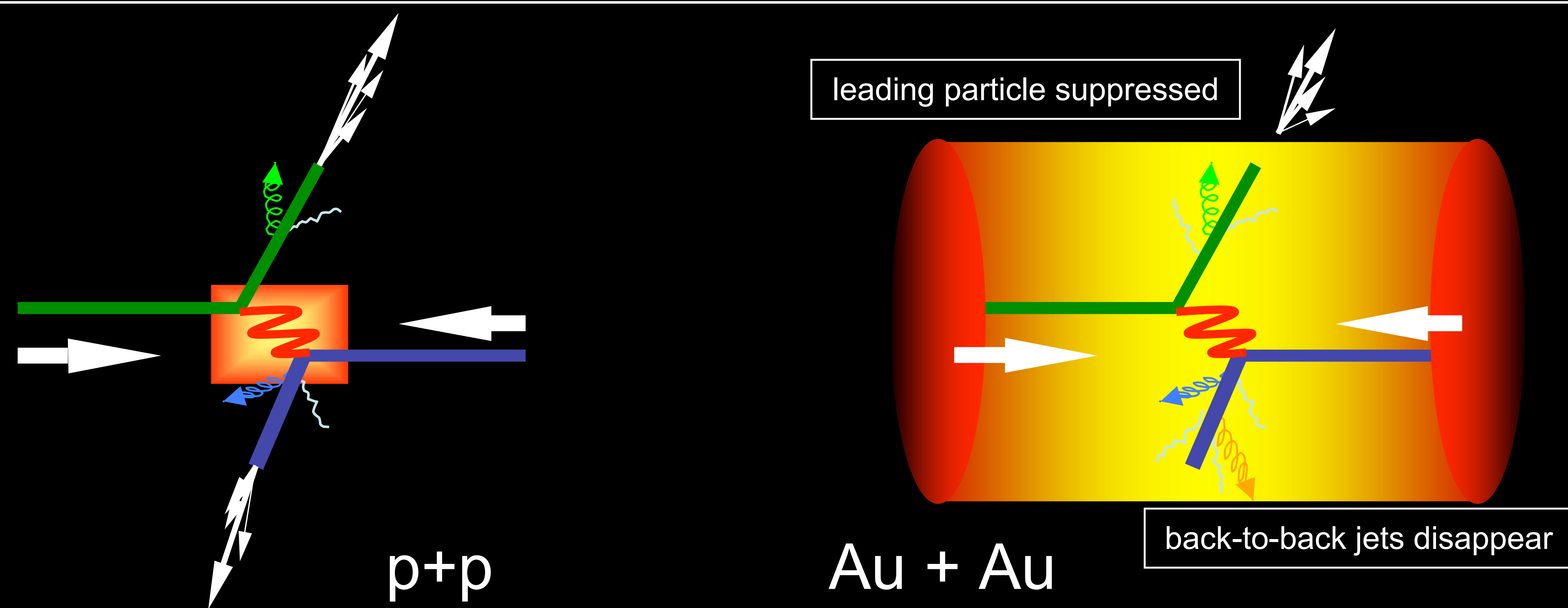
Experime ac

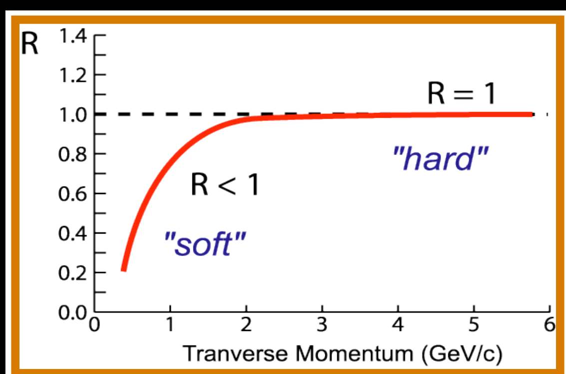
- **Energy**
- **Collect**
- Charm - productions plus the combination (1) and (2)

(1) Hard scattering production - QCD prediction
(2) Interactions with medium - deconfinement/thermalization
(3) Initial parton density

(1) Initial condition in high-energy nuclear collisions
(2) Cold-QCD-matter, small-x, high-parton density - parton structures in nucleon / nucleus

Energy Loss in A+A Collisions

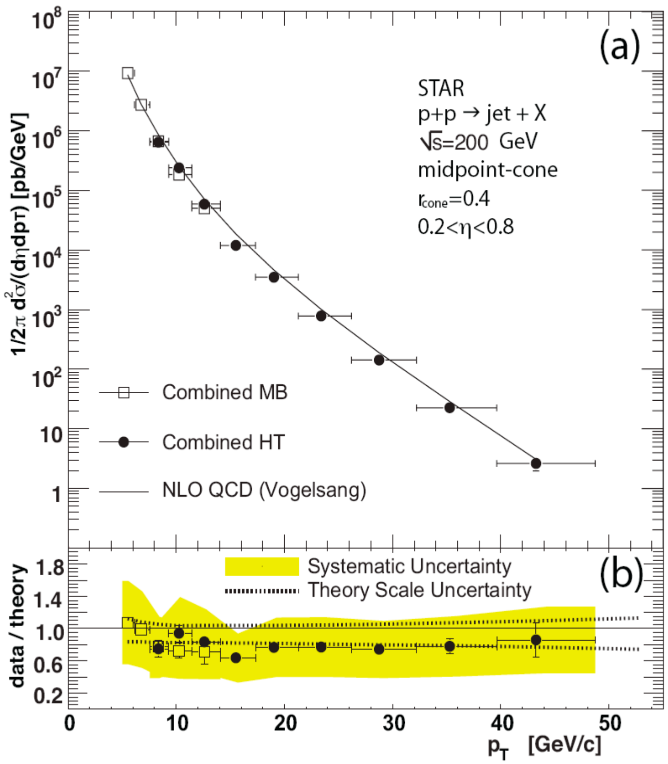


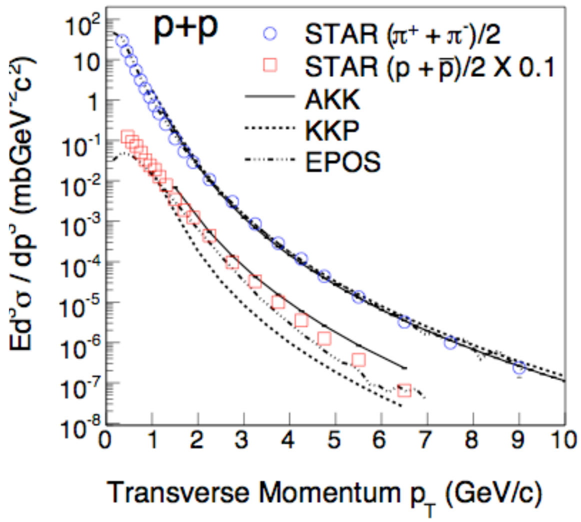


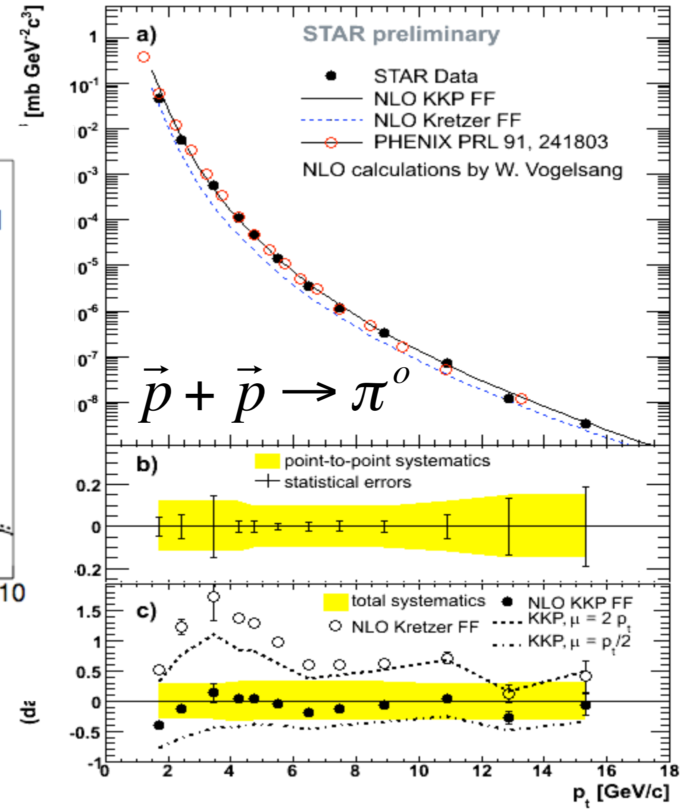
Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{NN}/dp_T d\eta}$$

Inclusive cross-section (jets, $\pi^{0,\pm}$,$p^{\pm}$)







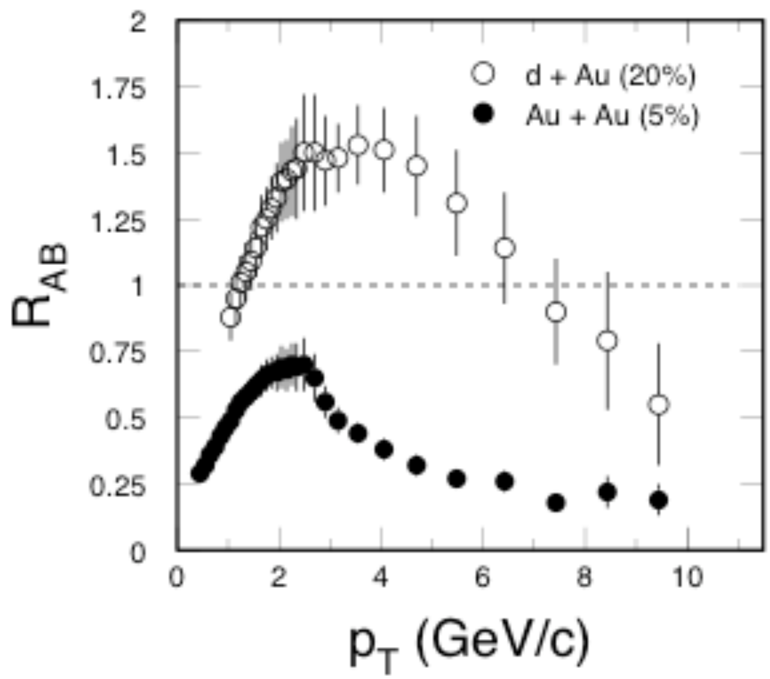
Mid-y jets, $\pi^{0,\pm}$ and $p^{\pm}$ productions are well reproduced by NLO pQCD calculations over many orders of magnitude ⇒

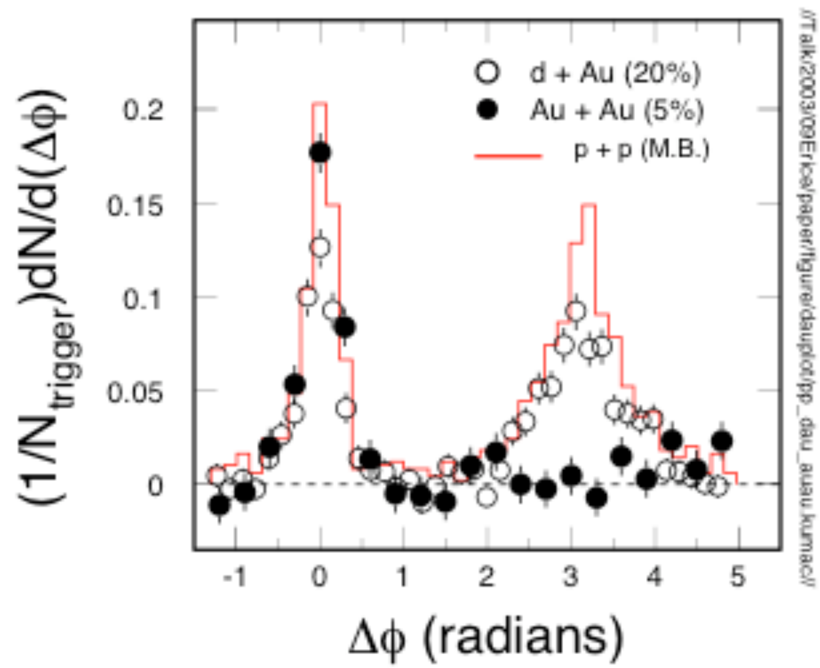
1) powerful tool for analyzing spin physics.

2) reliable reference for study high-energy nuclear collisions.

*STAR: PRL **97**, 252001(06); PL **B637**, 161(06)*

Suppression and Correlation





In central Au+Au collisions: hadrons are suppressed and back-to-back 'jets' are disappeared. Different from p+p and d+Au collisions.

Energy density at RHIC: ε > 5 GeV/fm^3 ~ 30ε_0

Parton energy loss:	Bjorken	1982
("**Jet quenching**")	Gyulassy & Wang	1992

…

Lesson Learned - QCD at Work

(1) Spectra at intermediate p_T show evidence of suppression up to $p_T \sim 10$ GeV/c;

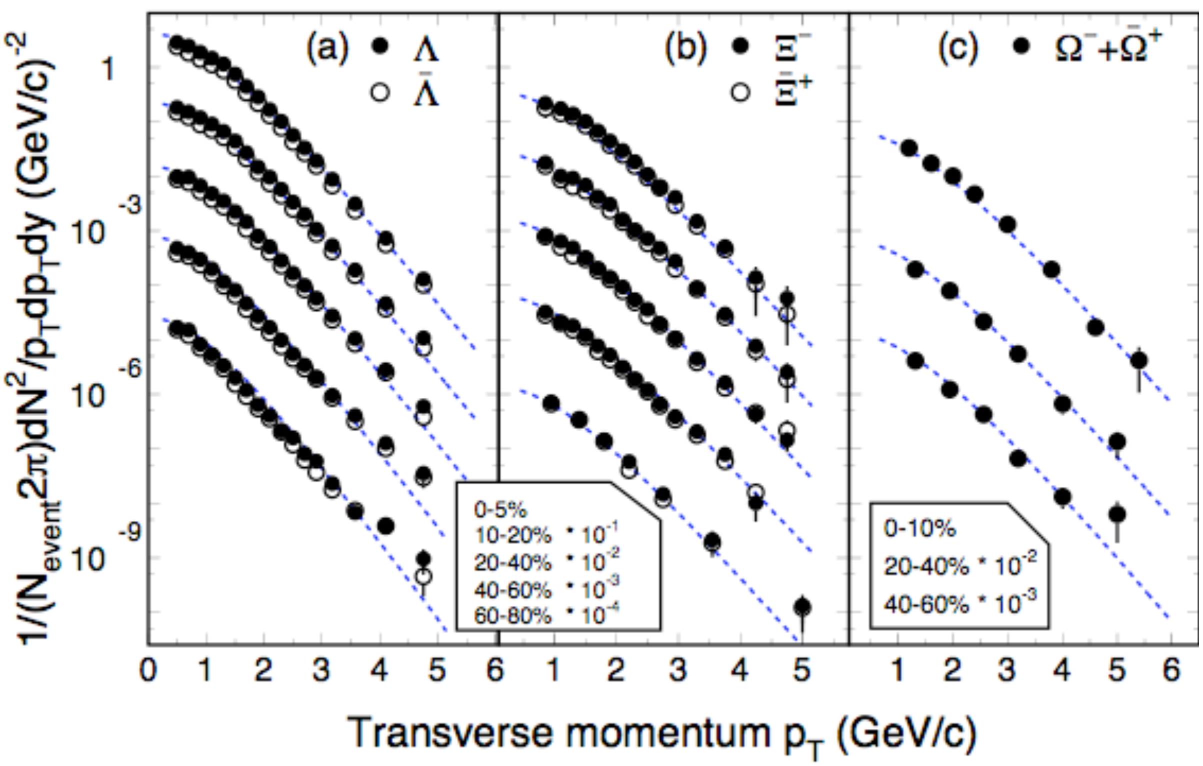
(2) Jet-like behavior observed in correlations:
- hard scatterings in AA collisions
- disappearance of back-to-back correlations;

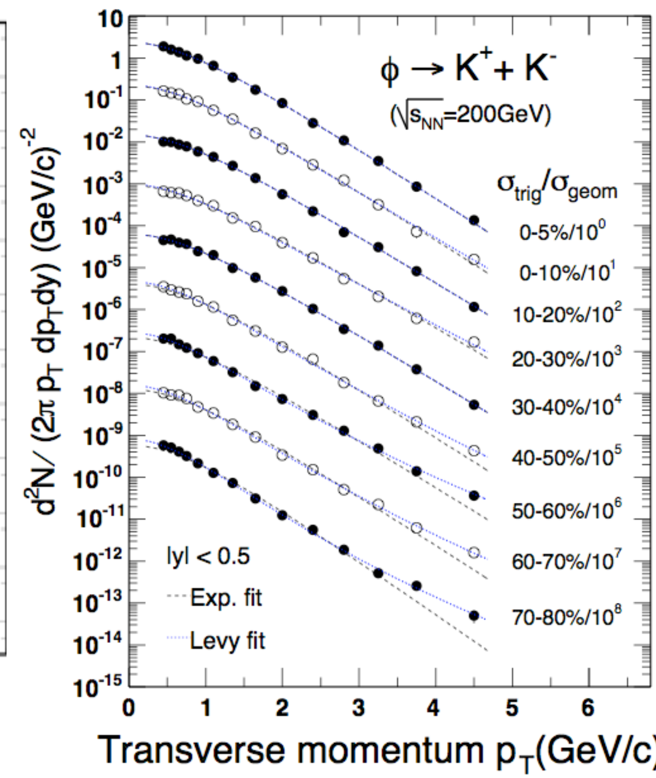
(3) Effect of color factors not yet observed

⇨ ***Energy loss processes should lead to progressive equilibrium in the medium***

STAR: Strange Hadrons

200 GeV Au + Au Collisions

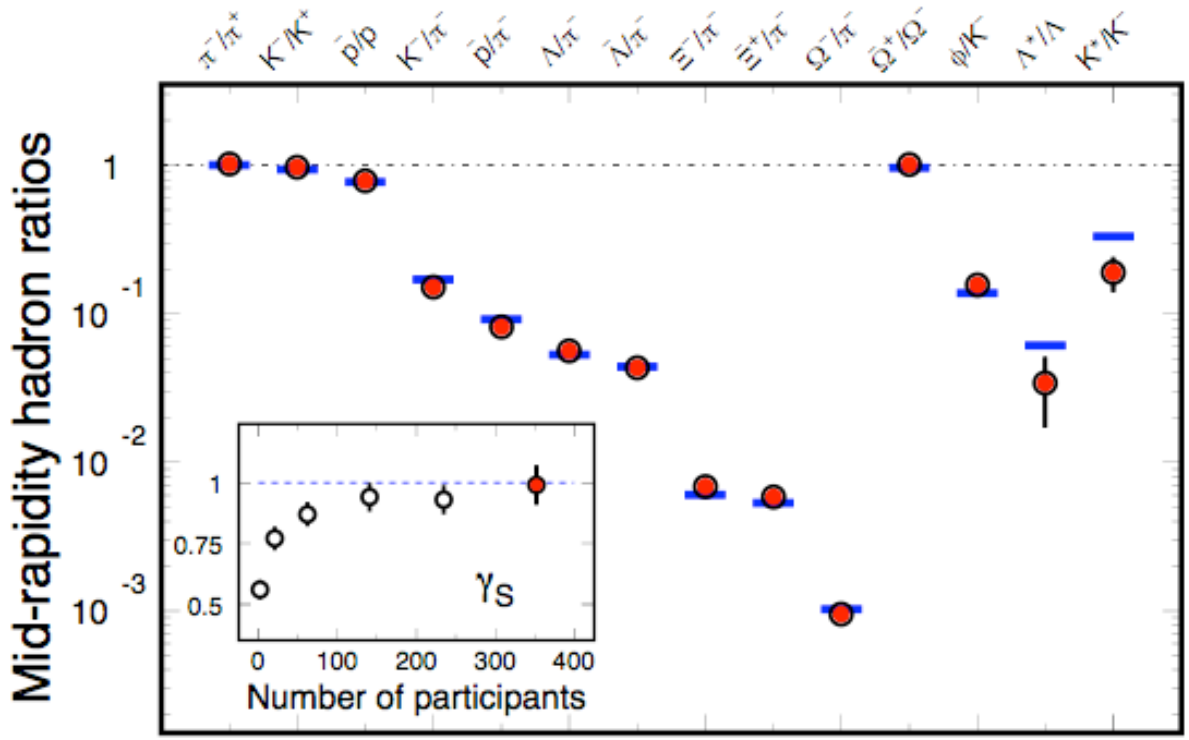




STAR: *J. Adams et al., PRL, **98**, 060301(07)*

PRL in print, 2007.

Yields Ratio Results



200 GeV ^{197}Au + ^{197}Au central collision

○ data

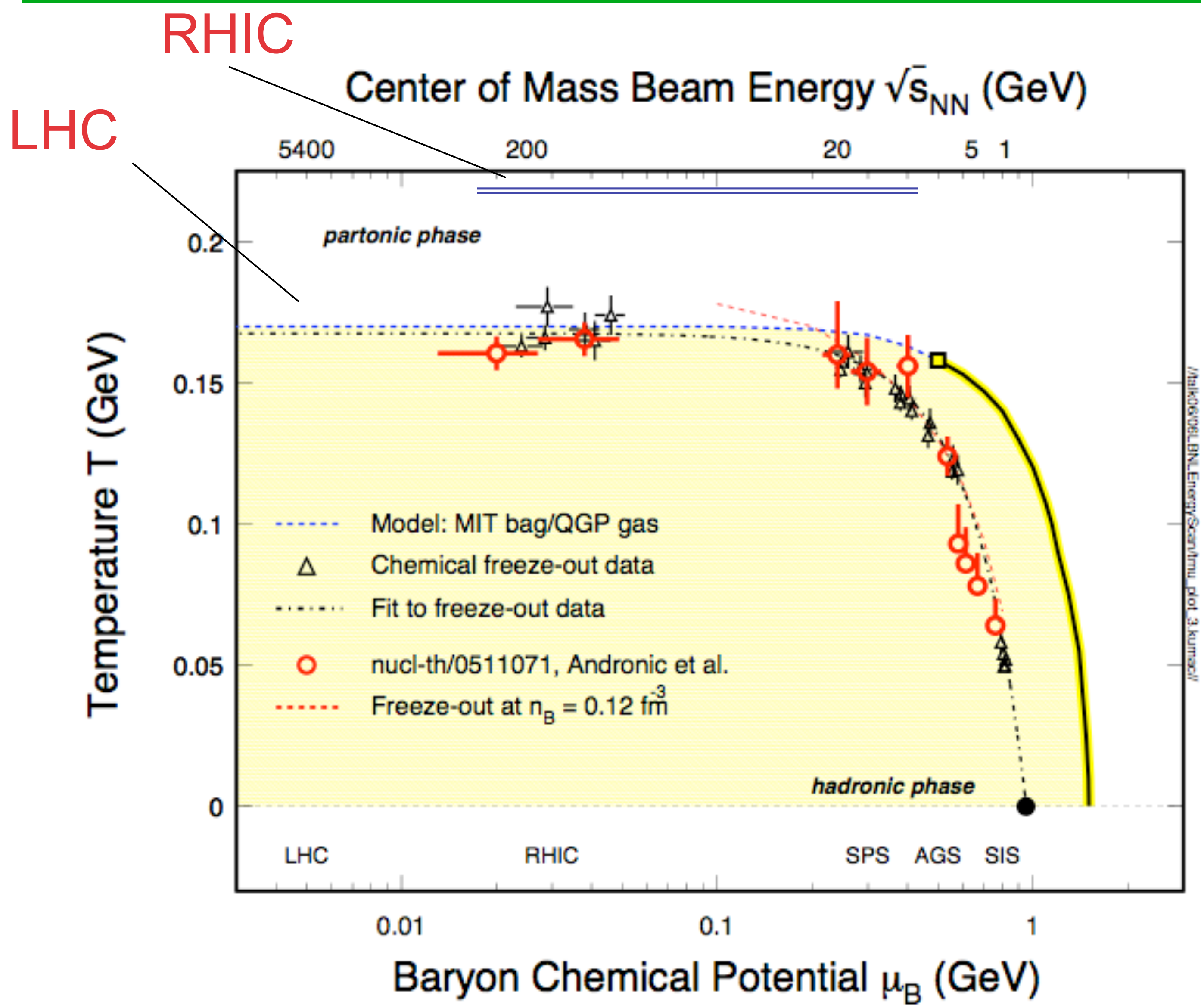
— Thermal model fits

T_{ch} = 163 ± 4 MeV

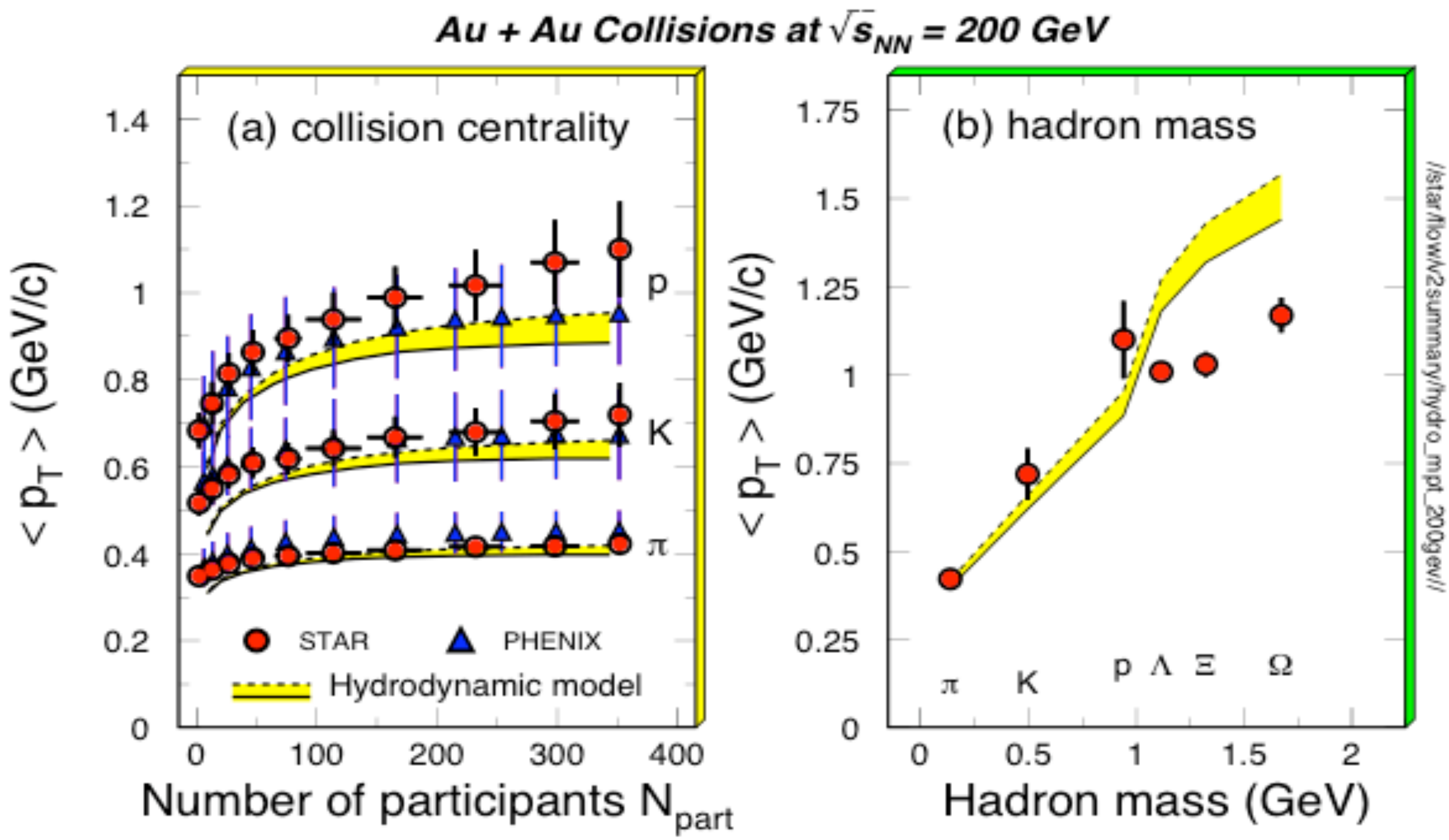
μ_B = 24 ± 4 MeV

- In central collisions, thermal model fit well with γ_S = 1. **The system is thermalized at RHIC.**
- Short-lived resonances show deviations. **There is life after chemical freeze-out.** RHIC white papers - 2005, Nucl. Phys. A757, STAR: p102; PHENIX: p184.

QCD Phase Diagram



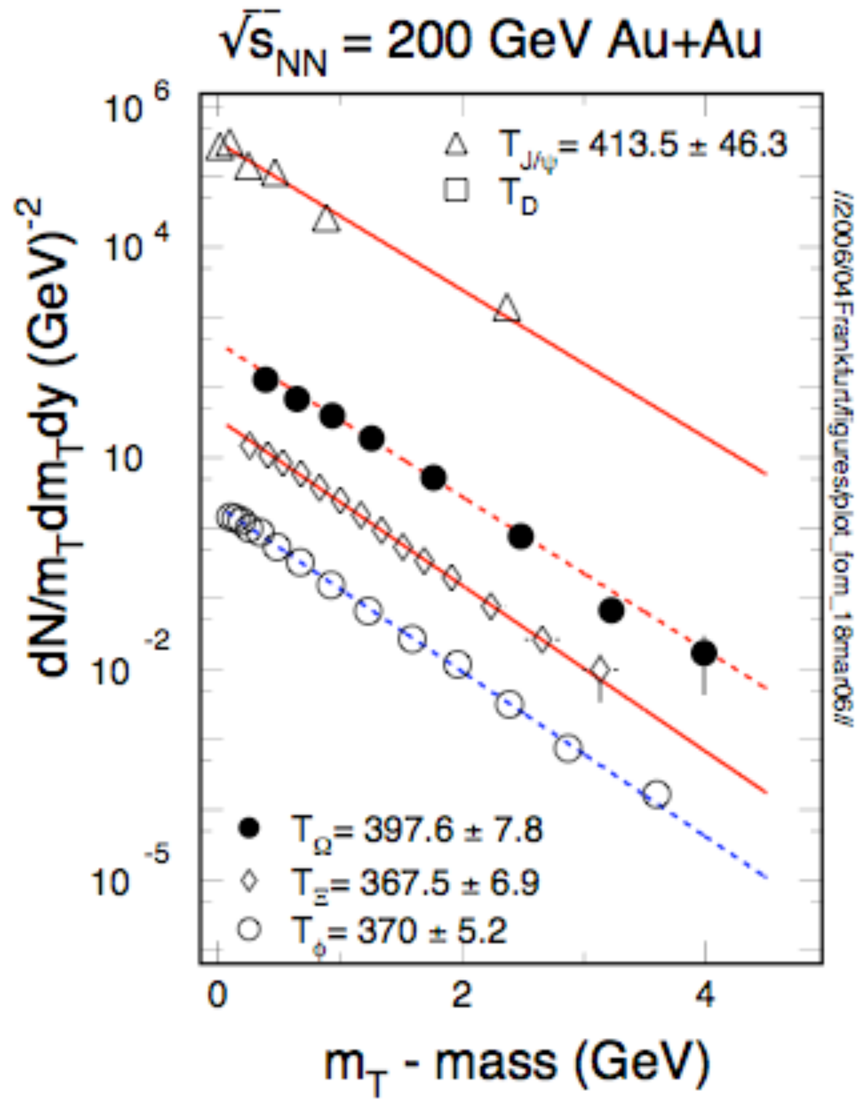
Compare with Hydrodynamic Model



- Hydrodynamic model fit to pion, Kaon, and proton spectra;
- Over predicted the values of <p_T> for multi-strange hadrons who are '***early*** freeze-out'

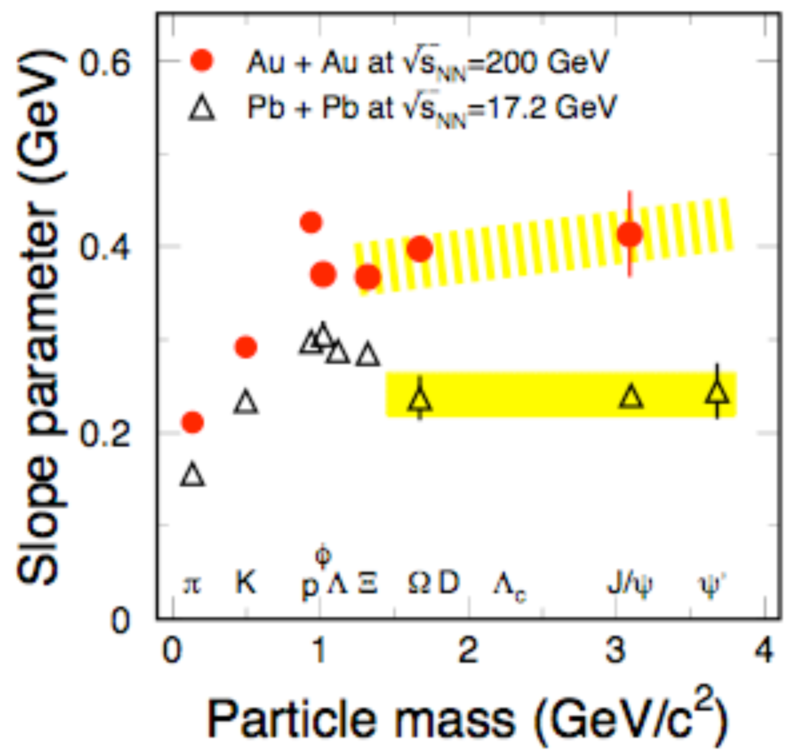
P. Kolab and R.Rapp, PRC

Slope Parameter Systematics



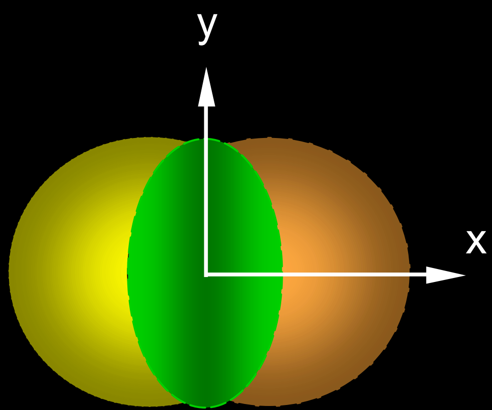
$$m_T = \sqrt{p_T^2 + m^2}$$

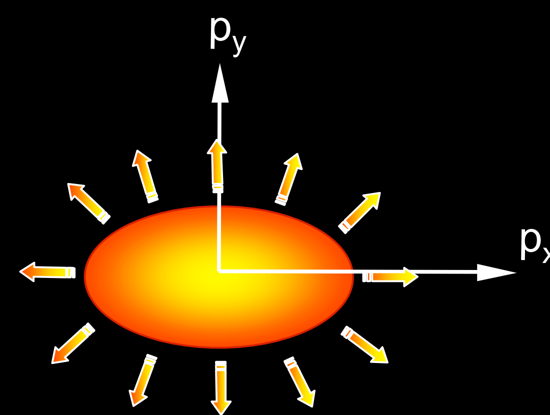
$$f \propto exp(-m_T/T_{slope})$$



Anisotropy Parameter v_2

coordinate-space-anisotropy ➪ momentum-space-anisotropy

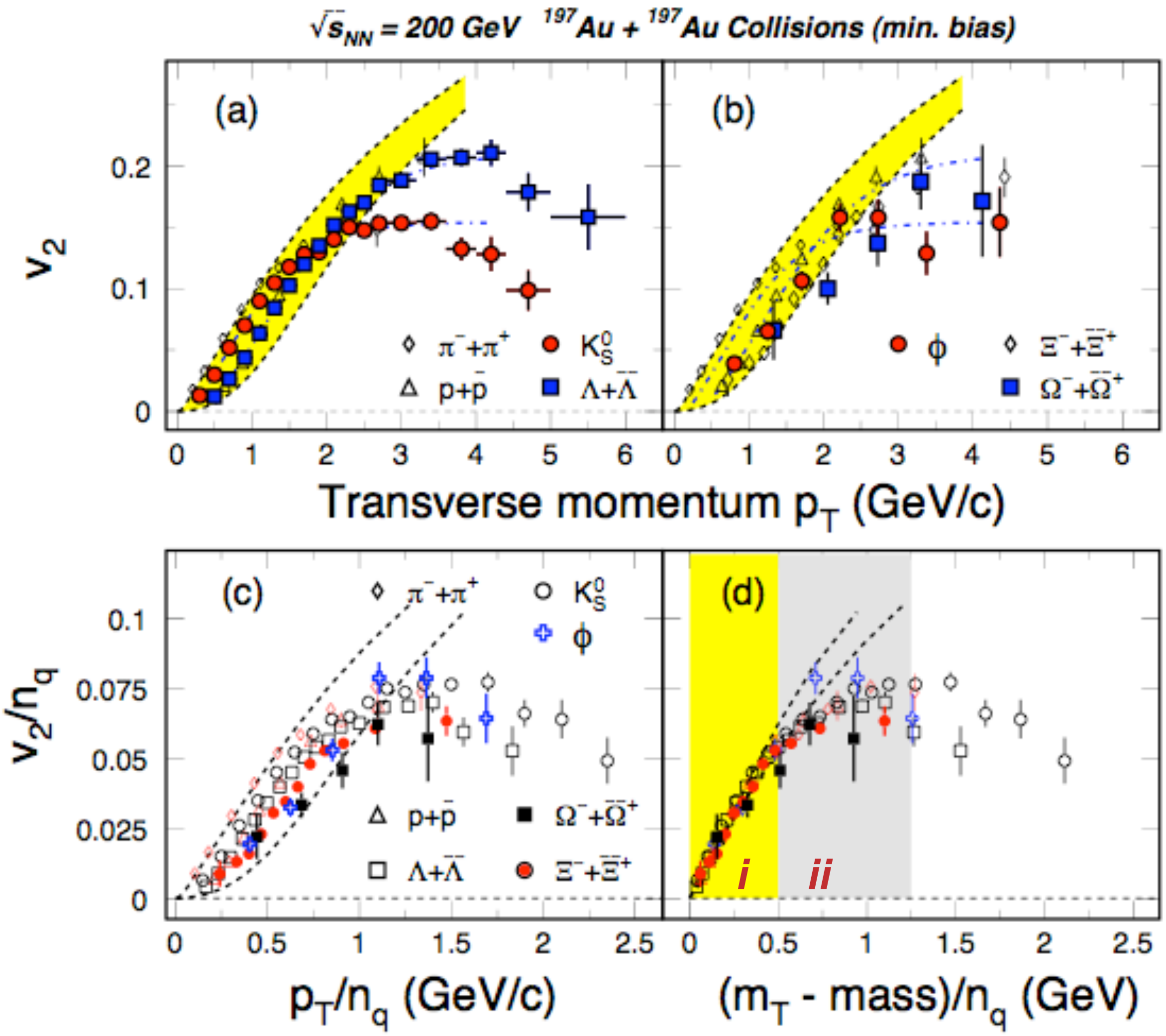




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

Collectivity, Deconfinement at RHIC



- v_2 of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

➪ **m_T - NQ scaling**

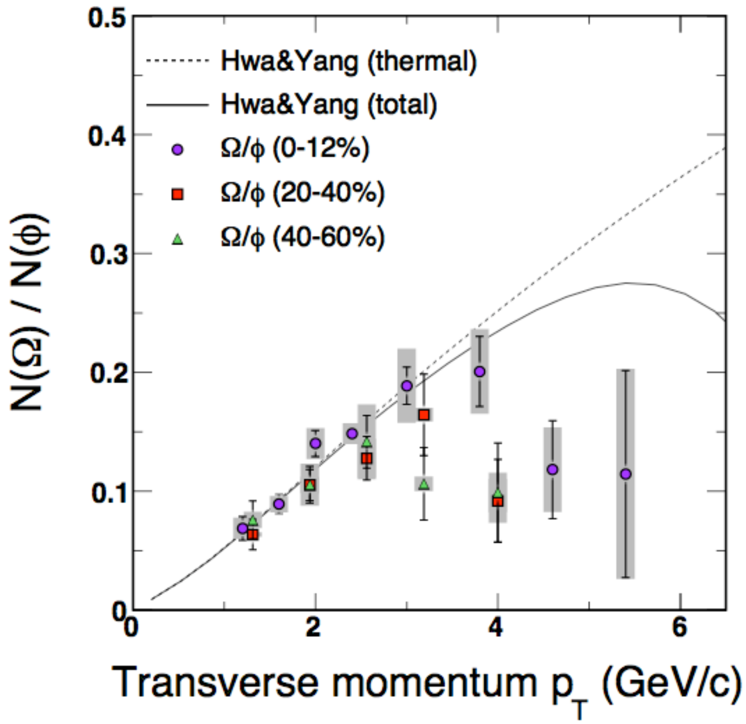
➪ **Partonic Collectivity**

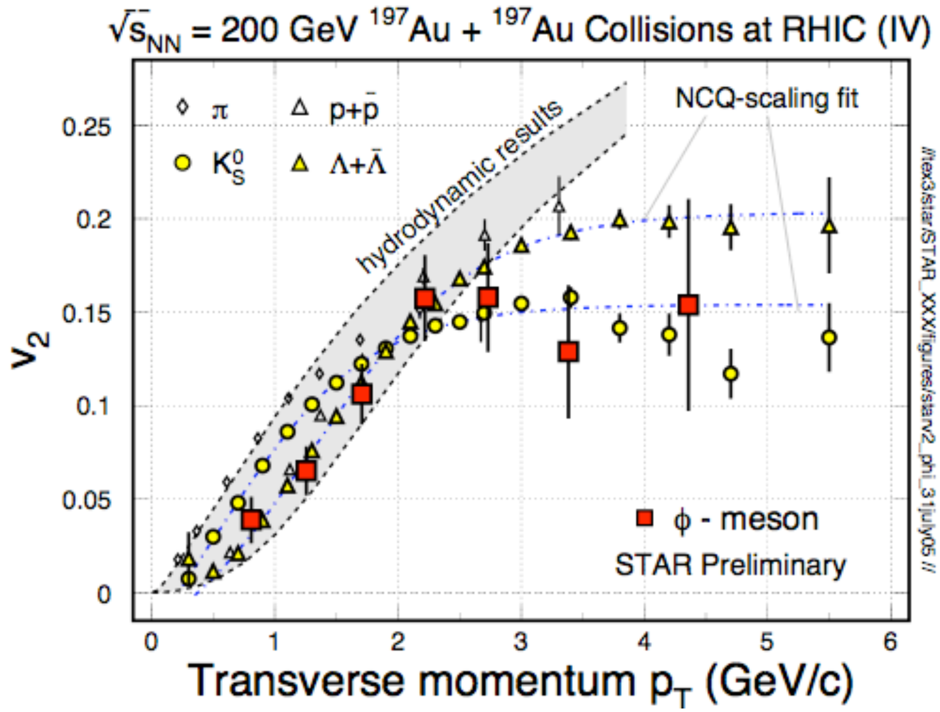
➪ **Deconfinement**

*PHENIX: PRL**91**, 182301(03)*
*STAR: PRL**92**, 052302(04), **95**, 122301(05) nucl-ex/0405022, QM05*

S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PR**C68**, 034904(03)*
Chen, Ko, nucl-th/0602025
*Nonaka et al. **PLB583**, 73(04)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
….

ϕ -meson Flow: Partonic Flow





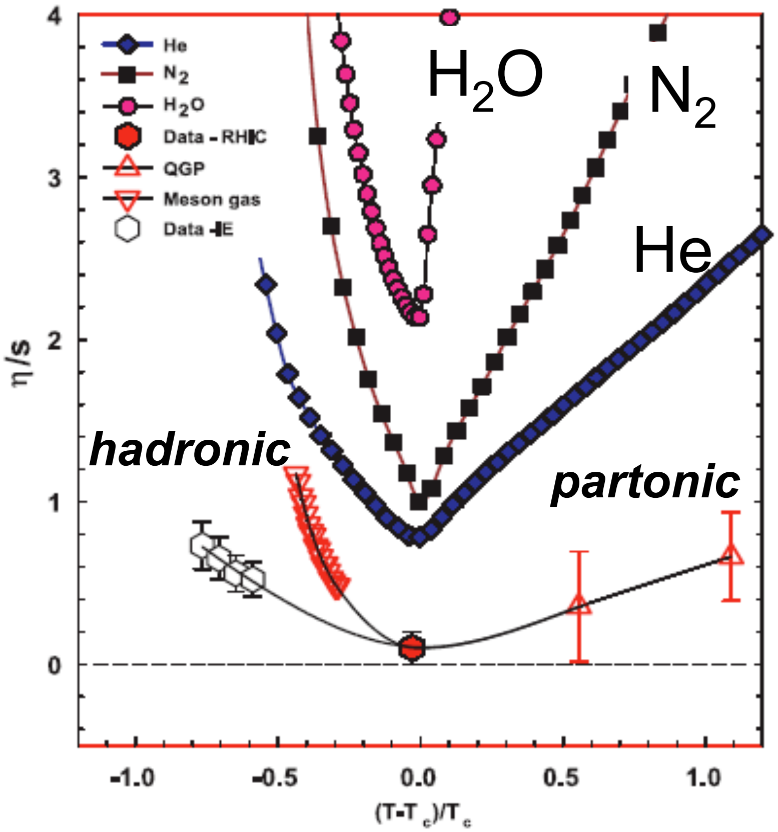
ϕ-mesons are special:

- they are formed via coalescence with thermalized s-quarks
- they show strong collective flow

'They are made via coalescence of seemingly thermalized quarks in central Au+Au collisions, the observations imply *hot and dense matter with partonic collectivity* has been formed at RHIC'

STAR: Phys. Rev. Lett., In print nucl-ex/0703033; Phys. Lett. B612, 81(2005)

Viscosity and the Perfect Fluid



Caption: The viscosity to entropy ratio versus a reduced temperature.

Lacey et al. PRL **98**:092301(07)
hep-lat/0406009
hep-ph/0604138

The universal tendency of flow to be dissipated due to the fluid's ***internal friction*** results from a quantity known as the **shear viscosity**. All fluids have non-zero viscosity. The larger the viscosity, the more rapidly small disturbances are damped away.

Quantum limit: $\eta/s_{AdS/CFT} \sim 1/4\pi$

pQCD limit: ~ 1

At RHIC: ideal ($\eta/s = 0$) hydrodynamic model calculations fit to data ⇒

Perfect Fluid at RHIC?!

Lesson learned II: EoS Results

In Au + Au collisions at RHIC:

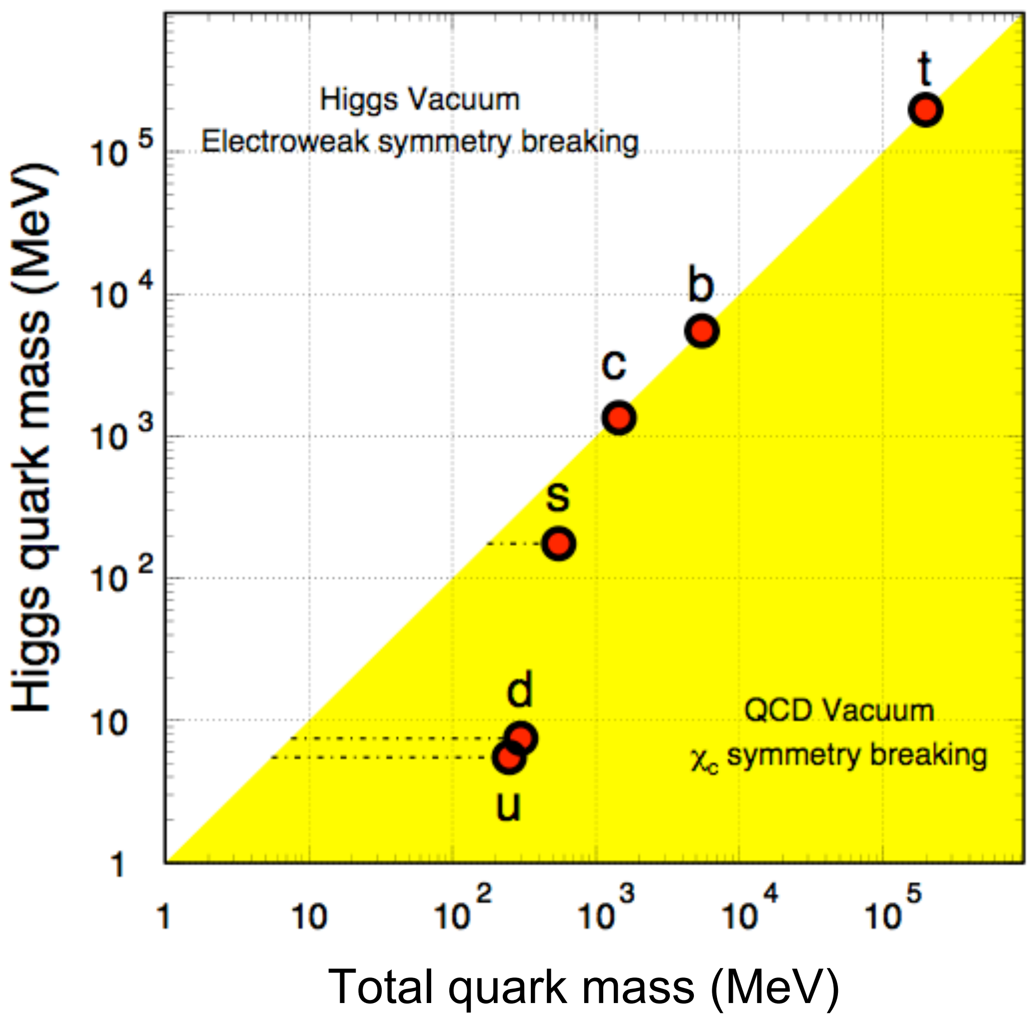
(1) Hadron yields in the state of equilibrium - chemical freeze-out near the transition temperature

(2) The yields N(Ω)/N(ϕ) ratios indicate thermalization

(3) **Partonic Collectivity** and de-confinement

⇨ ***Test light quark thermalization with heavy flavor probes***

Quark Masses



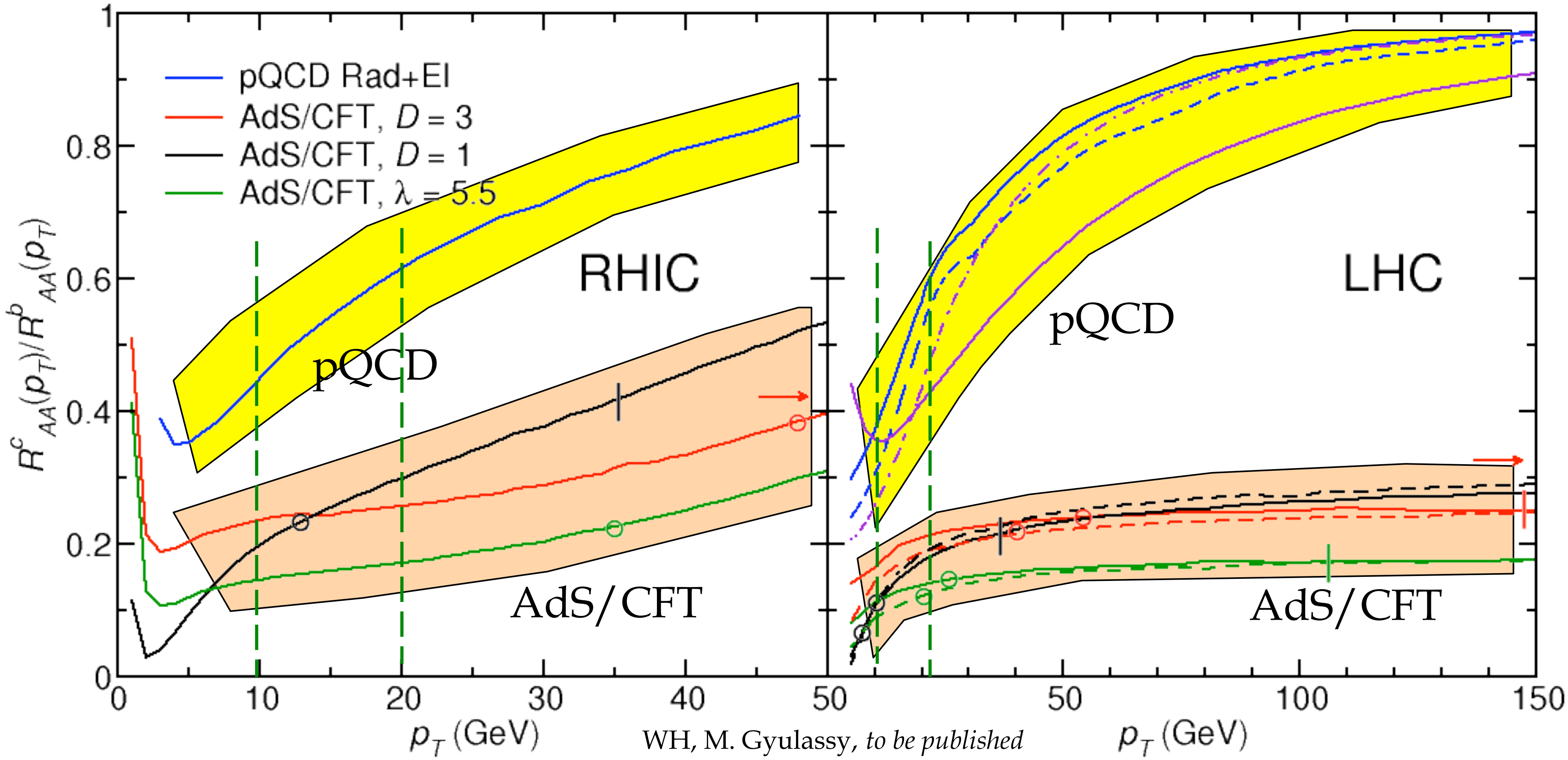
- Higgs mass: electro-weak symmetry breaking. (current quark mass)
- QCD mass: Chiral symmetry breaking. (constituent quark mass)

⇨ Strong interactions do not affect heavy-quark masses.

⇨ Important tool for studying properties of the hot/dense medium at RHIC.

⇨ Test pQCD predictions at RHIC, including the effect of color factors.

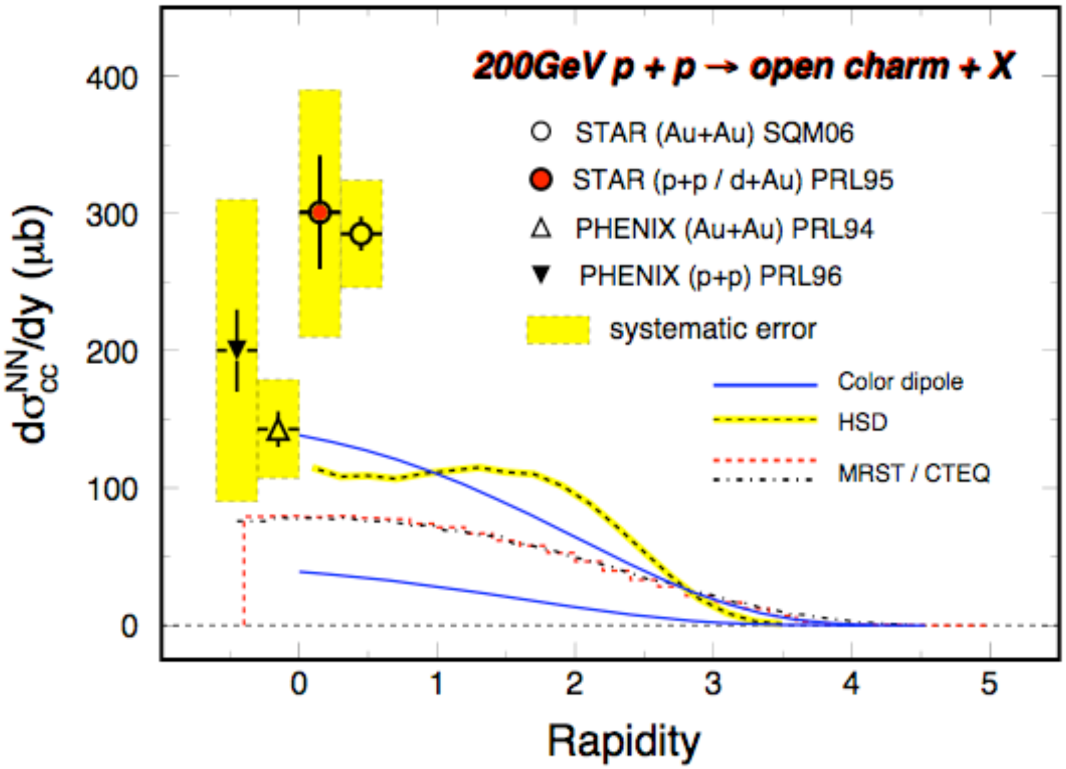
The R^{cb} Ratio: pQCD vs. AdS/CFT

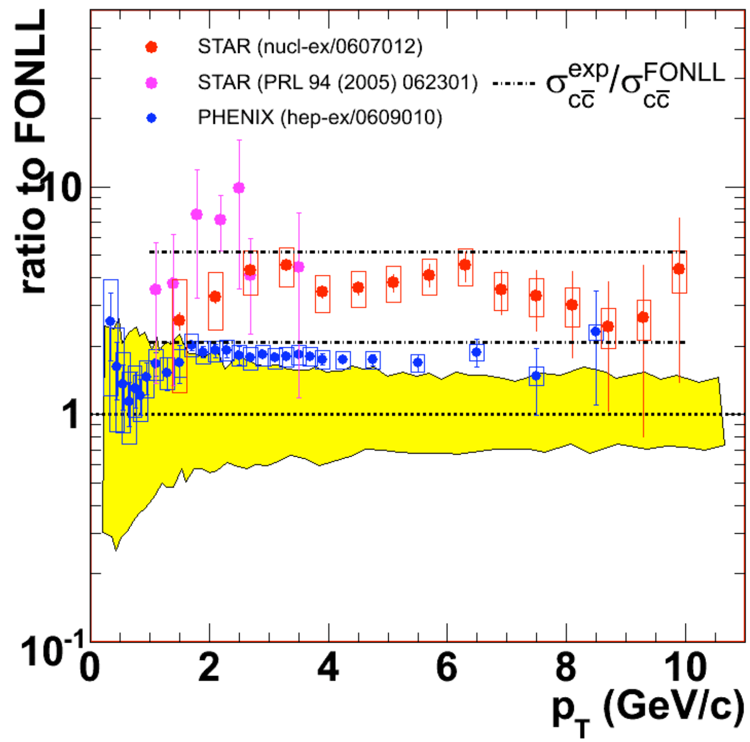


1) Ratio of Charm over Bottom ⇒ separate the energy loss mechanism and the limit on η(T)/s(T)
2) At RHIC, AdS/CFT more valid at higher p_T due to $T_{RHIC} < T_{LHC}$

W. Horowitz and M. Gyulassy, nucl-th/07062336

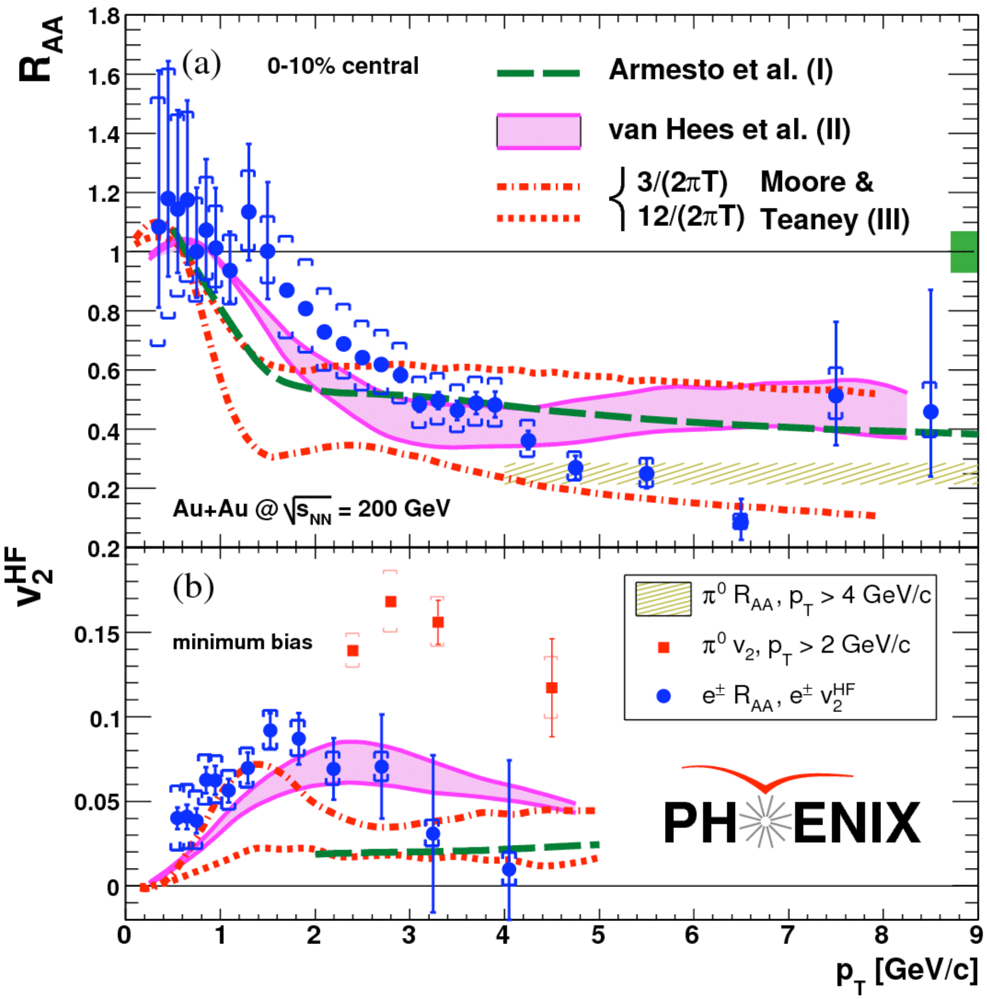
Charm Cross Sections at RHIC





1) Large systematic uncertainties in the measurements
2) Theory under predict by a factor ~ 2 and
STAR ~ 2 x PHENIX
3) Directly reconstructed charm hadrons ⇒Upgrades

HQ Decay Electron Data



Phenix: *PRL **98** 172301(07)*

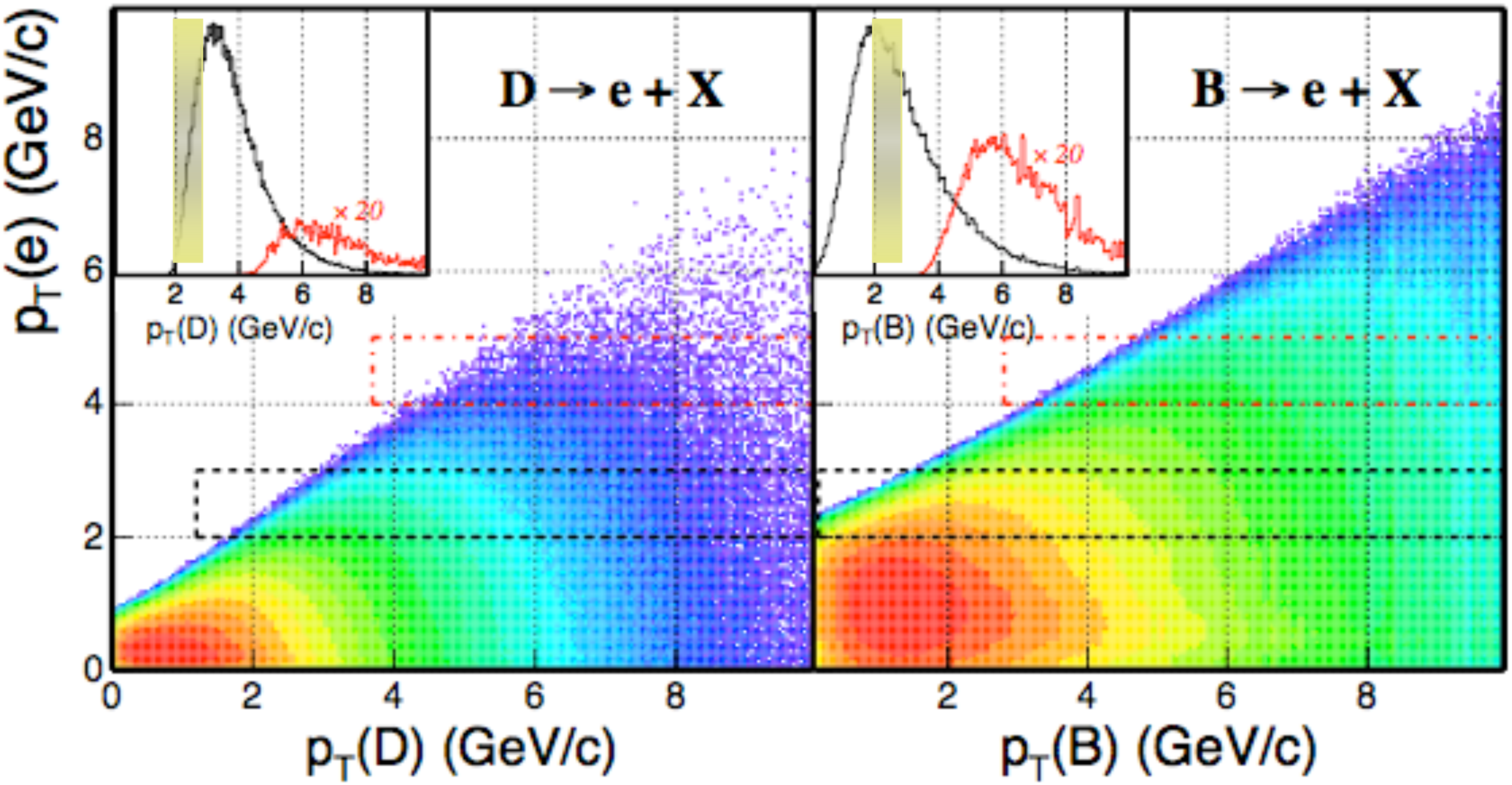
- Large p_T: suppression as light quark hadrons;
- Low p_T: non-vanishing v_2

⇒ Possible coupling of the heavy quarks with the hot/dense medium at RHIC.

Unknown: p_T dependence of the bottom quark contributions

Unknown: collectivities of light- and heavy-quarks

Decayed Electron p_T vs. b- and c-hadron p_T



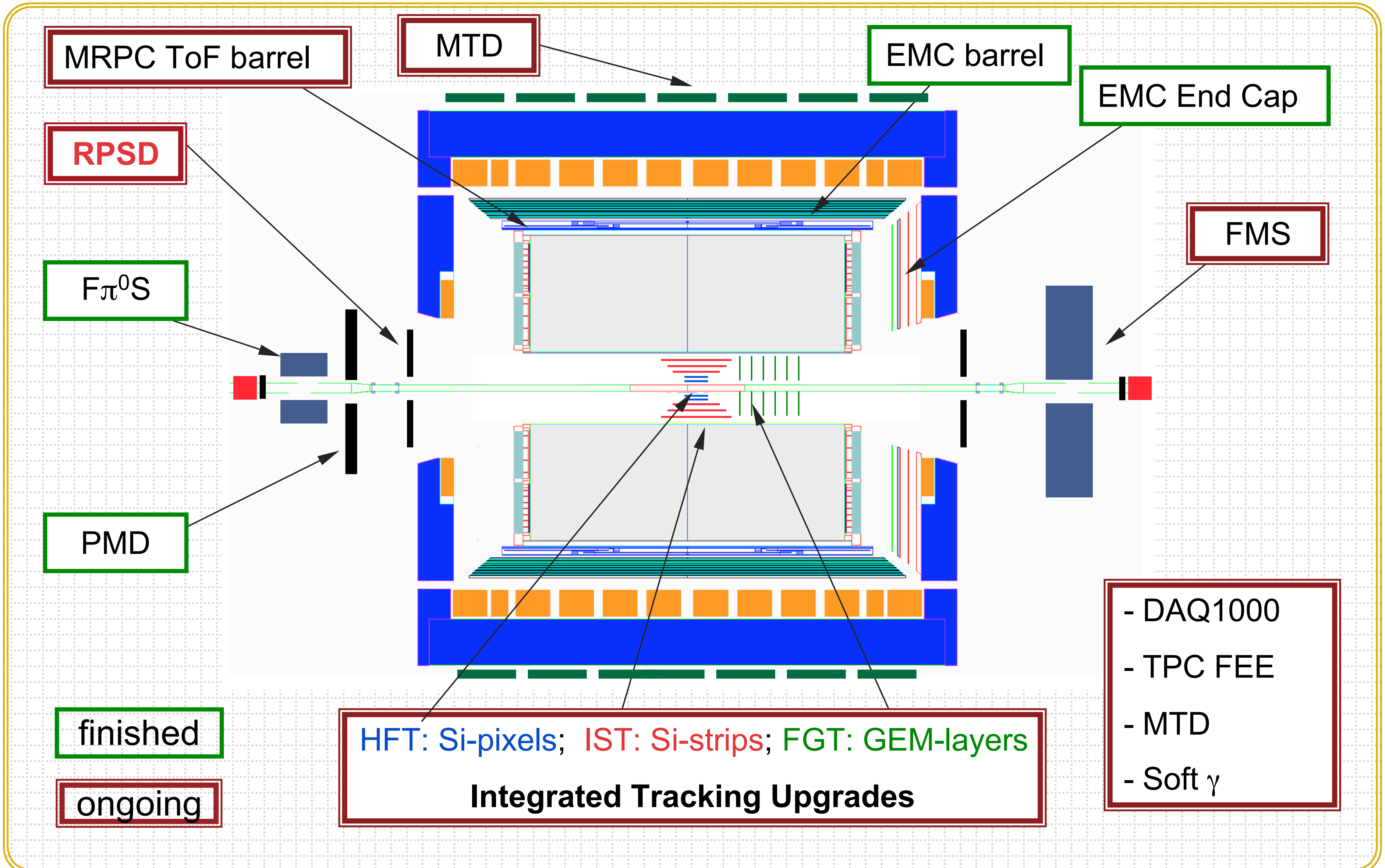
The correlation between the decayed electrons and heavy-flavor hadrons is weak.

Pythia calculation Xin Dong, USTC October 2005

Upgrades Are Needed!

When systematic error dominates the data, new experiments (detectors) are called for.

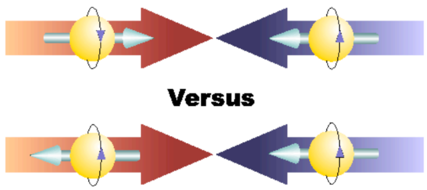
STAR Upgrades



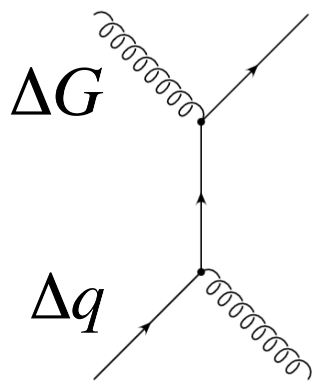
Heavy Flavor Tracker at STAR

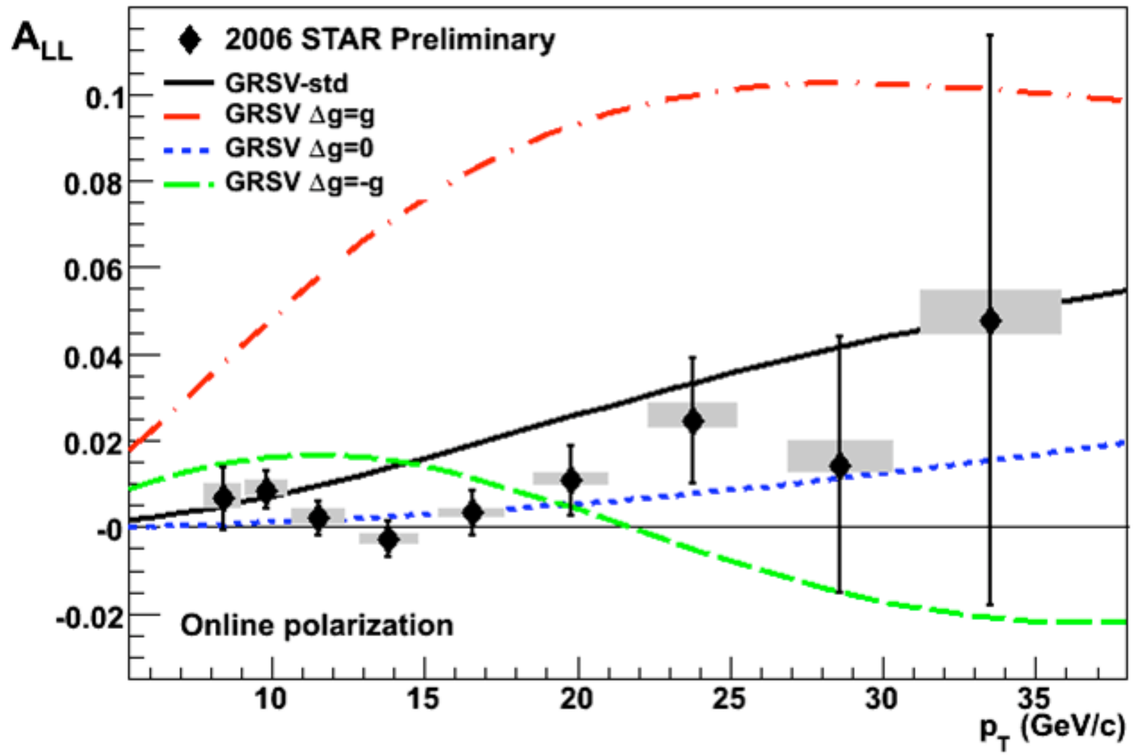
	Measurements	Requirements
Heavy Ion	heavy-quark hadron v_2, the heavy-quark collectivity	- High efficiency - Low p_T coverage - mid-rapidity - High counting rate
	heavy-quark hadron R_{AA}, heavy-quark energy loss	- High p_T coverage
p+p	energy dependence of the heavy-quark production	- Low p_T coverage
	gluon structure with heavy quarks and direct photons	- wide rapidity coverage

Recent Spin Results



$$\vec{p} + \vec{p} \rightarrow jet(s) + X$$

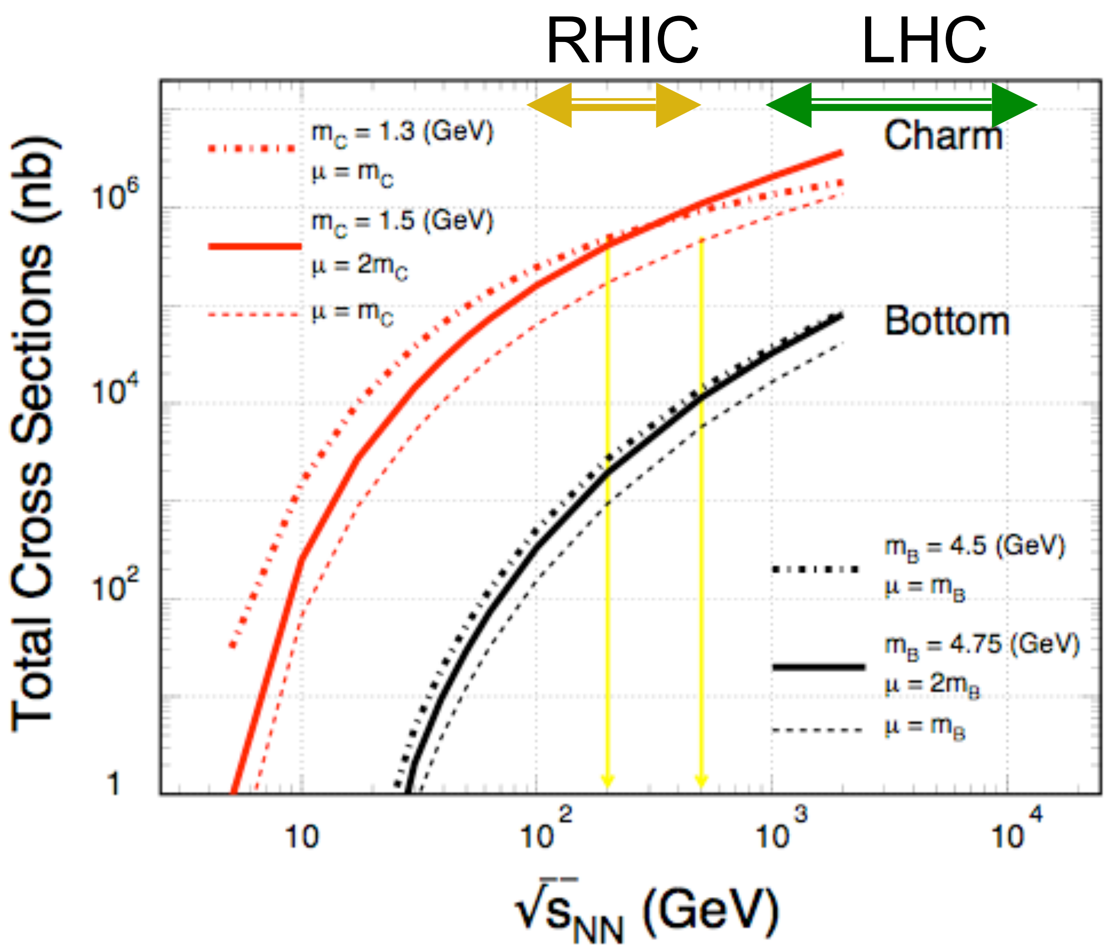




Summary: "… disfavor at 98% C.L. maximal positive gluon polarization in the polarized nucleon." *(2005 data)*

STAR: *"Longitudinal double-spin asymmetry …" arXiv: 0710.2048, sub. to PRL*
*(i) Phys. Rev. Lett. **99** (2007) 142003; (ii) Phys. Rev. Lett. **97** (2006) 252001*
*(iii) Phys. Rev. Lett. **92** (2004) 171801*

Heavy Quark Production



The NLO pQCD predictions of charm and bottom for the total p+p hadro-production cross sections.

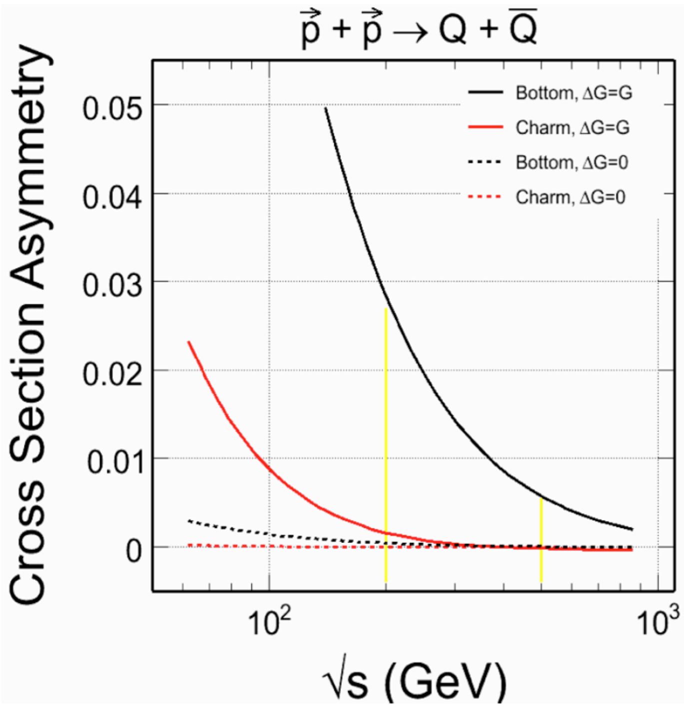
The renormalization scale and factorization scale were chosen to be equal.

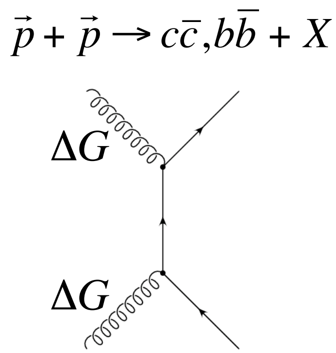
RHIC: 200, 500 GeV
LHC: 900, 14000 GeV

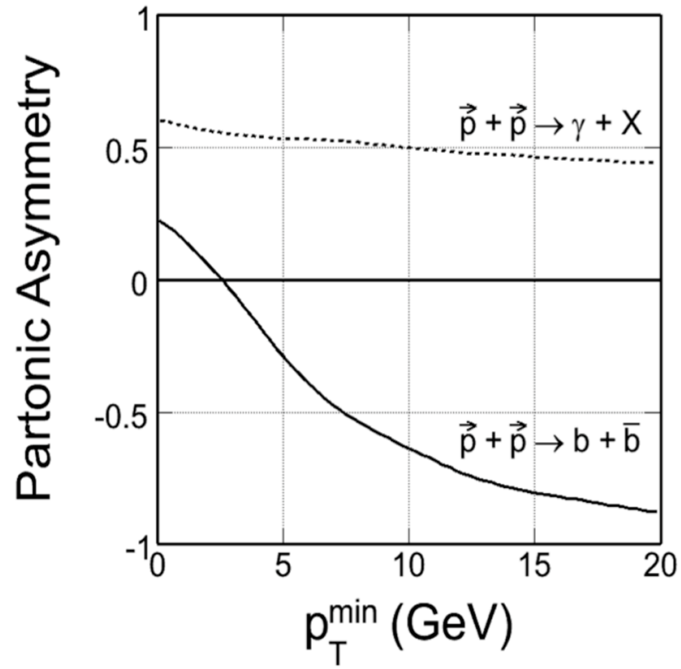
Ideal energy range for studying pQCD predictions for heavy quark productions.

Necessary references for both heavy ion and spin programs at RHIC.

Physics Program - HFT





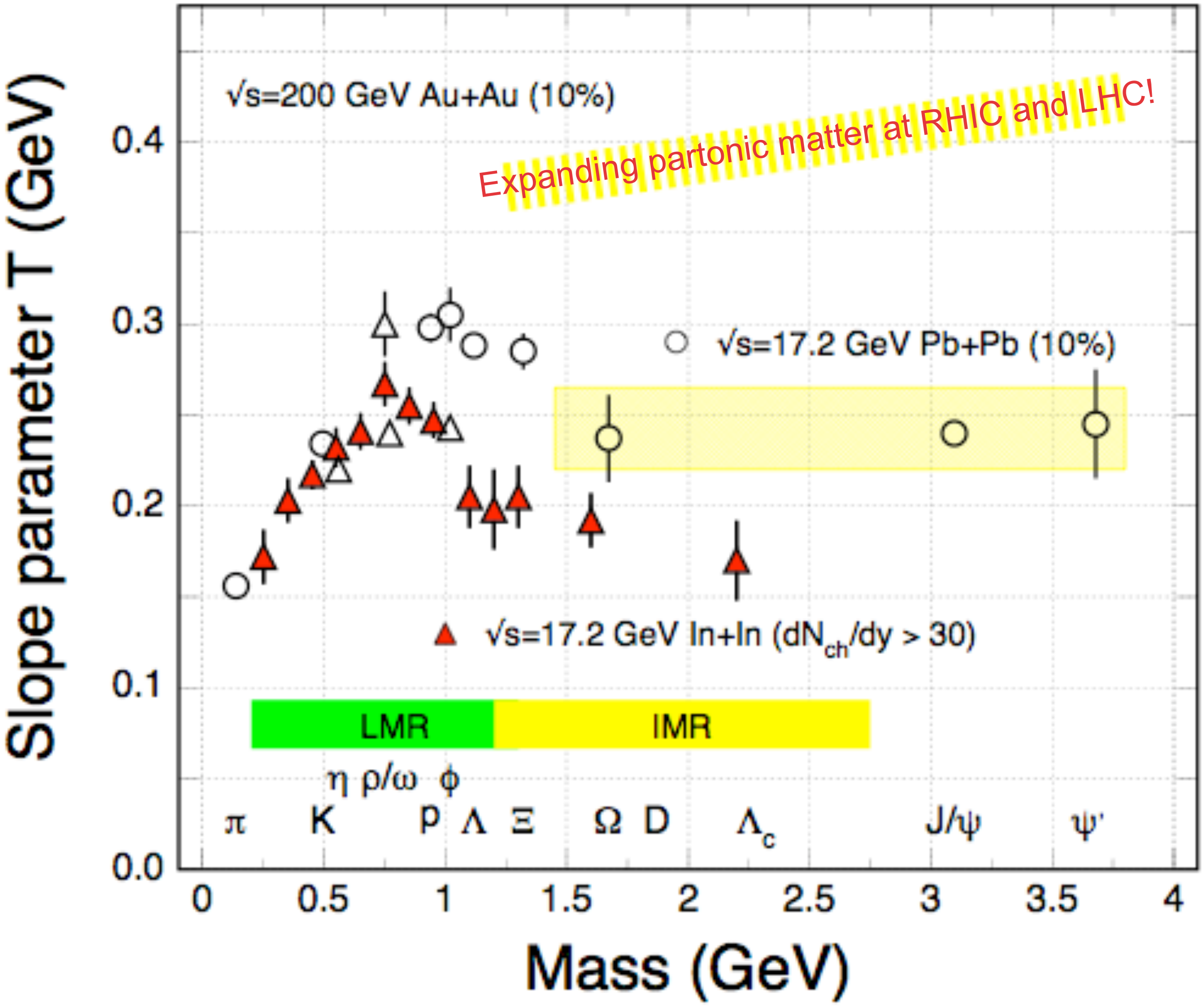


- Heavy quark production: Complimentary probe for gluon polarization and open the study of spin dynamics to quark mass.

- Partonic asymmetry on event kinematics - Never tested before!

- NU: needs references

Direct Radiation of Matter



The di-leptons will allow us to measure the direct radiation of matter with partonic degrees of freedom, no hadronization!

Puzzle 1: dramatic change of the slope parameter at $m \sim 1$ GeV

Puzzle 2: source of T at $m \geq 1.5$ GeV

Rates Estimate - v_2

(a) dN/dp_T distributions for D-mesons.

Scaled by $\langle N_{bin} \rangle = 290$, corresponds to the minimum bias Au + Au collisions at RHIC.

(b) Assumed v_2 distributions for D-mesons.

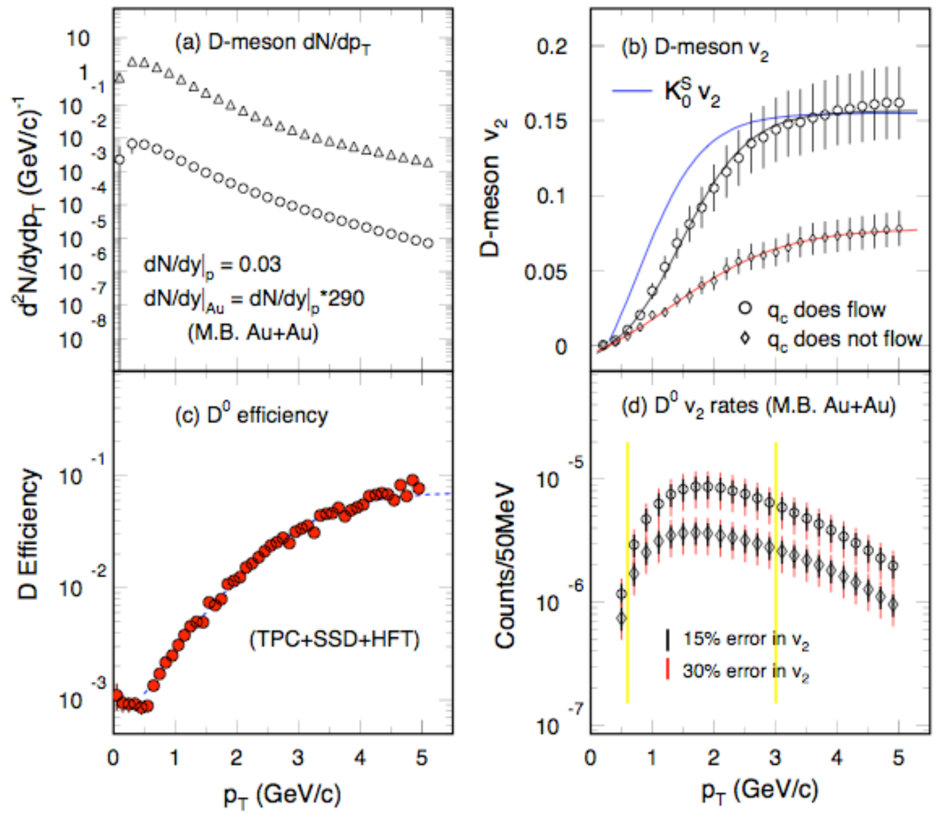
---- PLB 595, 202 (2004)

Error bars shown are from 15% systematic errors

(c) 3-σ significance D^0 efficiency with TPC+SSD+HFT.

(d) D^0 meson v_2 rates from minimum bias Au + Au collisions at 200 GeV.

The small and large error bars are for 15% and 30% systematic errors, respectively. For the v_2 analysis, 12 bins in φ are used.



p_T (GeV/c)	Δp_T (GeV/c)	# of Events q_c does flow	# of Events q_c does not flow
0.6	0.2	260×10^6	525×10^6
1.0	0.5	70×10^6	140×10^6
2.0	0.5	53×10^6	125×10^6
3.0	1.0	105×10^6	175×10^6
5.0	1.0	210×10^6	440×10^6

Physics of the Heavy Flavor Tracker at STAR

1) Au+Au collisions

- measure heavy-quark hadron v_2, the heavy-quark collectivity to study light-quark thermalization *(200 - 300 $x10^6$ Au+Au M.B.* events)*

- measure heavy-quark energy loss to study pQCD in hot/dense medium *(7.5 $x10^9$ p+p events; $1x10^8$ Au+Au 10% events; 5 $x10^8$ Au+Au M.B.* events)*

- measure di-leptions to study the direction radiation from the hot/dens medium

2) p+p collisions

- energy dependence of the heavy-quark production *(7.5 $x10^9$ events)*
- measure gluon structure with heavy quarks and direct photons *(300 - 800 pb^{-1} events)*

M.B: minimum bias*